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Socio-ecological changes on the Loess Plateau of China after Grain to Green Program

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HIGHLIGHTS

- Comprehensive assessment of the socio-ecological changes on the Loess Plateau
- LP has achieved "win-win" gains of restoring environment and promoting development.
- Degree of afforestation affects the changes of ecological factors on the LP.

GRAPHICAL ABSTRACT

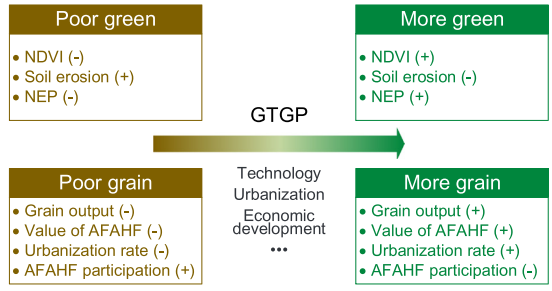

Illustration of the shift of the LP from poor green and poor grain to more green and more grain
("+" in the in the parenthesis means high value whereas "-" means low value)

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ABSTRACT

Payment for Ecosystem Services (PES) is now widely accepted as a policy tool for advancing both ecological and social progress. The Chinese government's Grain to Green Program (GTGP) is the world's largest PES program. It was initiated nearly 20 years ago to reverse previous environmental degradation. However, it is difficult to achieve both conservation and economic "win-win" gains, and care is needed in monitoring environmental and socioeconomic outcomes. Here we choose the Loess Plateau (LP), the area where GTGP was implemented most intensively, to study the social-ecological changes after GTGP and determine whether these changes are related to GTGP. The results show that LP has achieved "win-win" gains of restoring environment and promoting socioeconomic development: normalized difference vegetation index (NDVI) time series show a significant greening trend, and soil retention and carbon sequestration services have improved from 2000 to 2015. Simultaneously, grain output from the LP has increased by 56.7%. We also analyzed the effects of afforestation on changes of socio-ecological factors, and find that the changes of NDVI, soil erosion, and carbon sequestration mainly reflect the degree of afforestation rather than climate change, while the correlations between changes of socioeconomic factors and degree of afforestation are insignificant. We conclude that, despite some adverse outcomes such as water yield reduction, GTGP in LP has achieved considerable overall success in environmental factors. However, comprehensive and quantitative evaluation of the social impacts of GTGP is needed, as the impacts are clouded by multiple socioeconomic factors.

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1. Introduction

Sustainable development means economic growth that is environmentally and socially sounds (Sachs and Reid, 2006). Restoring degraded ecosystems while simultaneously achieving social and economic development goals is a challenge in many regions of the world (Adams et al., 2004; Tallis et al., 2008; Cao et al., 2009; Alix-Garcia et al., 2018). Ecosystem services are an ideal concept for linking human well-being and biophysical ecosystem properties because it promotes both practical conservation and economic development (Tallis et al., 2008). Payments for Ecosystem Services (PES) have become an important tool for balancing the ambitions of different regions and the relationships between nature and human beings (Wunder et al., 2018). It includes several different mechanisms, user-financed, government-financed and compliance—across the domains of water, biodiversity, and forest and carbon management around the world (Salzman et al., 2018). Nevertheless, an analysis of World Bank projects with objectives of alleviating poverty and protecting biodiversity revealed that only 16% made major progress on both objectives (Tallis et al., 2008). Scientific advances in quantifying the production of ecosystem services and tradeoff mechanisms are needed, and appropriate monitoring is necessary, if PES projects are to successfully achieve "win-win" outcomes that meet both environmental and social goals (Tallis et al., 2008).

The Grain to Green Program (GTGP) is one of the world's biggest programs offering PES (Liu et al., 2008; Wang et al., 2017). It has important global implications because it addresses a wide array of environmental issues as well as socioeconomic challenges. GTGP has been underway for the past 20 years. Previous studies have analyzed the effectiveness of GTGP in China, and found that overall ecological effects are beneficial and socioeconomic effects are mostly positive, the GTGP has increased vegetative cover, enhance carbon sequestration, controlled soil erosion, and changed income structure of participating households (Liu et al., 2008; Ouyang et al., 2016; Bryan et al., 2018). These studies also identified key characteristics of program success, providing experiences and lessons for the development, implementation, and sustainability of other PES programs within China and around the world (Liu et al., 2008; Bryan et al., 2018). However, the specific impacts of PES programs are often clouded by the confounding effects of multiple socio-economic, policy, and environmental factors (Lu et al., 2015; Ouyang et al., 2016; Bryan et al., 2018). Evaluations of specific outcomes of individual PES programs are required at multiple scales (Bryan et al., 2018).

Here we study the Loess Plateau (LP) (Fig. 1a), a region where the fragile environment is sensitive to climate change and human disturbance. The LP was the largest sediment source for the Yellow River providing nearly 90% of the sediment load (Wang et al., 2015) and for a long time was notorious for its severe droughts, erosion, sparse vegetation, high population pressure, low agricultural productivity and the poverty of the local farmers. To solve the issues facing the LP, the Chinese government has implemented many land management projects (Fu et al., 2017). The LP was prioritized as a pilot region for GTGP in 1999, and is the area where the GTGP has been most intensively implemented — significantly changing the landscape (Lu et al., 2012) (Supplementary Fig. S1) and affecting the ecosystem services (Lu et al., 2012; Feng et al., 2013; Jiang et al., 2016).

In this study, our objective is to identify the social-ecological changes in the LP after the GTGP and to determine whether these changes are related to the GTGP. We selected normalized difference vegetation index (NDVI) and several ecosystem services (soil

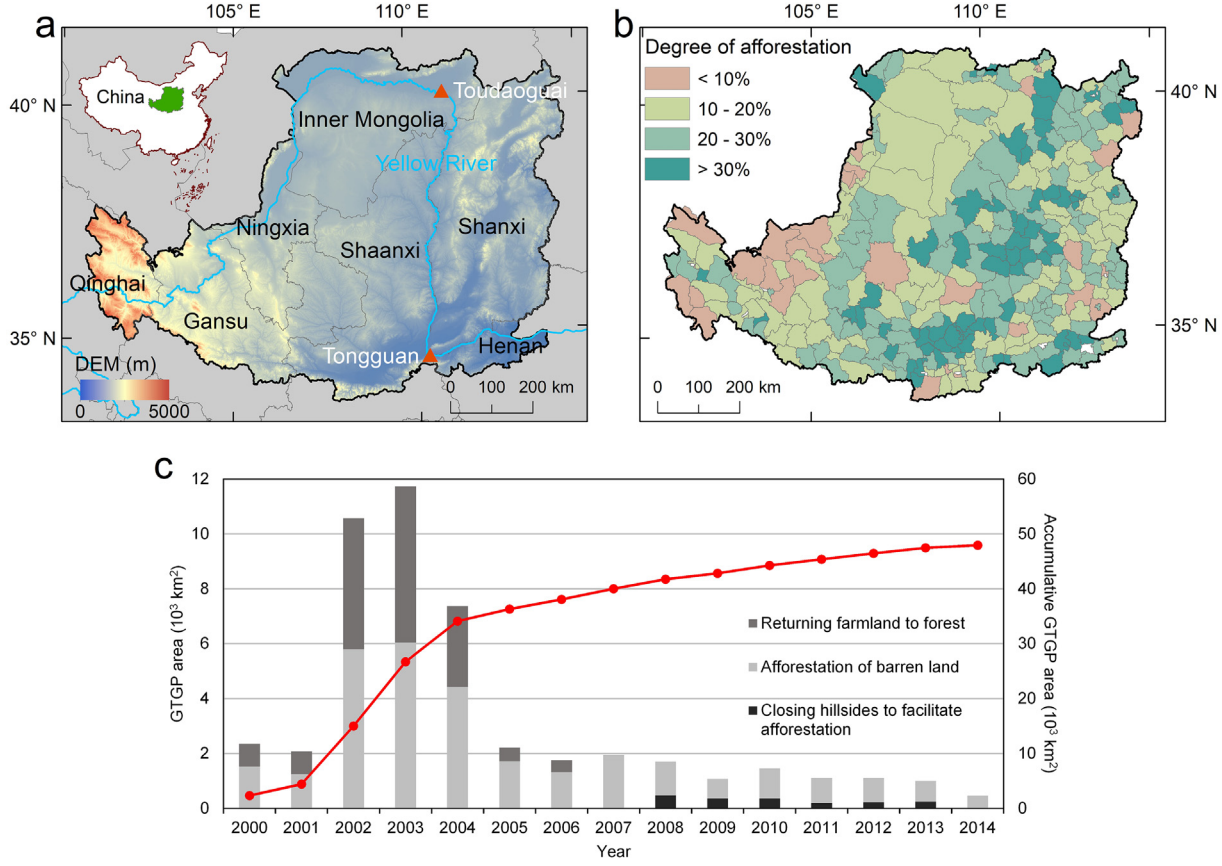

Fig. 1. Location of the LP and the spatial distributions of GTGP on the LP. (a) Boundary of the LP and location of the seven provinces on the LP. (b) Degree of afforestation of counties with >100 km^2 area. (c) Land area under GTGP from 2000 to 2014 in Shanxi, Shaanxi, and Ningxia province.

retention, carbon sequestration, and water supply) as ecological factors and grain output, gross output value of agriculture, forestry, animal husbandry and fishery (AFAHF), population, rural employment, and urbanization rate as social factors. Several assessment methods and statistical data were used to assess selected socio-ecological factors in the LP and their changes after the GTGP. Then we used partial correlation and correlation analyses to determine the relevance of these changes to the GTGP.

2. Materials and methods

2.1. Study area

The Loess Plateau (LP) in central China is the largest and deepest loess deposit in the world, covering approximately 640,000 km^2. It covers parts of seven provinces of China, including all of Shanxi and Ningxia, almost all of Shaanxi, and parts of Gansu, Inner Mongolia, Qinghai, and Henan (Fig. 1a). The LP is located in the temperate continental monsoon climatic zone of eastern Eurasia. The annual precipitation of the LP is commonly <500 mm, increasing from <300 mm in the northwest to 700 mm in the southeast (Fu et al., 2017). Annual mean temperatures range from 4 to 14 °C (Su and Fu, 2013). The LP is a typical water-limited landscape with evaporation accounting for 85% of the precipitation (Feng et al., 2016). The loess soil provided the agricultural foundation for early Chinese civilization about 7000 years ago (Fu et al., 2017); but the intensive agricultural activities over the past few thousand years have resulted in serious soil erosion with the once flat plateau now dominated by a hill-and-gully landscape (Liang et al., 2015). The area was trapped in a vicious circle of extensive degradation, leading to deeper impoverishment, which in turn led to more degradation (Fu et al., 2017).

2.2. Design and implementation of GTGP

The GTGP is designed to transfer farmland on steep slopes to forest or grassland to increase vegetation coverage and reduce soil erosion, and thus to restore regional ecosystems (Wang et al., 2017). Shaanxi and Gansu provinces in the LP were selected as pilot region of the GTGP in 1999. Then the program expanded to all provinces in the LP in 2000. GTGP is paid for by the central government; it directly engages millions of rural households as core agents of project implementation, with the stated principals of volunteerism (Bennett, 2008; Guo et al., 2014). The government offered farmers 1500 kg of grain (or 2100 yuan at 1.4 yuan per kg of grain from 2004) per ha of converted farmland per year on the LP. In addition, a 300 yuan per ha per year living allowance and a one-time grant of 750 yuan per ha for seeds or seedlings were provided. The duration of these subsidies depends on the outcome of farmland conversion: 2 years if the farmland is converted into grassland, 5 years if converted into commercial forest, or 8 years if converted to ecological forest (Liu et al., 2008). After the first phase, the government subsidies are renewed in a second phase, offering 1050 yuan for grain subsidy and 300 yuan for living subsidy per ha per year. The second phase subsidies for the different farmland conversions are the same as in phase one.

There are >300 counties in the 7 provinces on the LP (Fig. 1b). Shanxi, Shaanxi, and Ningxia province make up the main part of the LP. By the end of 2014, >45 billion yuan (in 2014 6.10 yuan = US$1) had been invested by GTGP in the three provinces (Supplementary Fig. S2): 36.69 billion yuan were paid in grain subsidies, and 6.62 billion in direct grants to farmers, and 2.72 million rural households per year were involved during 2001 to 2013 (Supplementary Table S1). By 2014 the total forested area was 47.93 × 10^3 km^2, of this 33.4% is converted from farmland and 62.7% from afforestation of barren land (Fig. 1c).

2.3. Data sources

2.3.1. Satellite time series data

The NDVI data sets used are Advanced Very High-resolution Radiometer (AVHRR) Global Inventory Monitoring and Modeling Systems (GIMMS) NDVI and Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI. The AVHRR GIMMS NDVI data from 1982 to 2015 were obtained from the Ecological Forecasting Lab at the National Aeronautics and Space Administration Ames Research Center (Pinzon and Tucker, 2014). The spatial resolution is 8 km × 8 km, and the temporal resolution is 15-days. The MODIS NDVI data from 2000 to 2015 were obtained from the National Aeronautics and Space Administration Earth Observing System (Huete et al., 2011) with a spatial resolution of 1 km × 1 km and a 16-day interval. The two annual NDVI data sets used in our research were obtained using the maximum value composite (MVC) method. The annual evapotranspiration (ET) data of the LP from 2000 to 2014 were extracted from MOD16 global evapotranspiration data sets (Mu et al., 2011), the spatial resolution is 1 km × 1 km.

2.3.2. Meteorological and hydrological data

Daily average air temperature and annual precipitation from the National Meteorological Administration of China for 2000–2015 were obtained from 172 stations within and near the LP (Feng et al., 2016), and interpolated onto a 1 km × 1 km grid covering the entire LP by Kriging method. Annual runoff and sediment load data at the Toudaoguai and Tongguan gauging stations on the Yellow River (2000–2015) were taken from the Yellow River Water Resources Bulletin (Wang et al., 2015).

2.3.3. GTGP and socioeconomic data

The statistics of GTGP in each province from 2000 to 2014 and the annual area of afforestation in each county from 2002 to 2014 were obtained from the Chinese Forest Statistical Yearbook (Cao et al., 2018). The output of grain, gross output value of agriculture, forestry, animal husbandry and fishery (AFAHF), number of rural employees and AFAHF employees in 2000 and 2015 were collected at county level from the China Statistical Yearbook (County-level) and Statistical Yearbook of each province (Lu et al., 2012). The population data of the LP, including permanent residents and urban population, were derived from the 5th and 6th national censuses at county level in 2000 and 2010 (Cao et al., 2018). The urbanization rate was calculated as the ratio of urban population to the number of permanent residents. Agricultural conditions of Shanxi, Shaanxi, and Ningxia province in 2000 and 2015 were collected from the China Statistical Yearbook (Lu et al., 2015).

2.4. Determining social-ecological changes on the LP

2.4.1. Detecting breakpoint in vegetation index

To detect the abrupt change time of NDVI trends, the breakpoint in the AVHRR GIMMS NDVI time series from 1982 to 2015 was analyzed using a piecewise linear regression (PLR) method at the LP and pixel scale. PLR is a statistical method that allows switching regressions to give separate results for several segments of an independent variable (Malash and El-Khaiary, 2010). We use PLR to perform linear regression in two segments, and the boundaries between the segments are the breakpoints. The breakpoint value with the smallest estimate of error variance (σ^2) of the regression lines was selected. We defined a significant breakpoint as occurring when either p value of the two regression lines before and after the breakpoint is <0.05. If the slope of fitted lines of NDVI is more than zero, it is regarded as a greening trend, while a slope of less than zero is regarded as a browning trend. According to the change of trend and slope before and after breakpoint, the NDVI trend changes can be divided into 6 types: green to greener, greener to green, green to brown, brown to green, brown to browner, and browner to brown (Supplementary Fig. S3b, S3c).

2.4.2. Assessment of ecosystem services

We used soil erosion to reflect the change of soil retention service on the LP. Annual soil erosion amounts from the LP from 2000 to 2015 were assessed by the Universal Soil Loss Equation (USLE). Annual soil loss A (t ha^{-1} yr^{-1}) can be expressed mathematically as: $A = R \times K \times LS \times C \times P$, where R is the rainfall erosivity (MJ mm ha^{-1} h^{-1} yr^{-1}), K is the soil erodibility (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the slope length and gradient factor, C is the cover management factor, and P is the support practice factor. For methods used to calculate each factor see references (Fu et al., 2011; Wu et al., 2016). Sediment load of the middle reach of the Yellow River from 2000 to 2015 were also analyzed to reflect the change of soil erosion on the LP. We used the difference between sediment load of the Toudaoguai station and Tongguan station (Fig. 1a) to calculate the sediment load of the middle reach of the Yellow River.

We used net ecosystem productivity (NEP) to reflect carbon sequestration service on the LP. NEP was calculated as the difference between net primary production (NPP) and soil heterotrophic respiration (Rh). We calculated NPP at 8 km × 8 km spatial resolution over the LP for the period 2000–2015 using the terrestrial Carnegie–Ames–Stanford approach (CASA) ecosystem model (Yu et al., 2009). To estimate heterotrophic respiration, we calculated soil total respiration first by developing the 'NPP-T-SW' model, which is the empirical relationship established between 111 measured annual soil respiration data over China collected from various datasets (Bondlamberty and Thomson, 2010; Bond-Lamberty and Thomson, 2014) or published papers (Chen et al., 2010; Xie et al., 2014) and annual simulated NPP, monthly mean temperature (T) and average surface soil water (SW). Soil respiration can be afterwards converted to heterotrophic respiration by using a linear regression model fitted by using the collected sites' measurements.

To reflect the changes of water supply service, the MODIS ET data of the LP from 2000 to 2014 and runoff coefficient between the Toudaoguai station and Tongguan station were analyzed. The runoff coefficient was calculated as the ratio of runoff (mm) to precipitation (mm) of the catchment between Toudaoguai station and Tongguan station.

2.4.3. Statistical analysis of social-ecological factors

To analyze the trend of ecological factors (i.e. NDVI, soil erosion, sediment load, NEP, ET, and runoff coefficient), we calculated linear regression relating series of each ecological factor with time (year), and the result was tested at a significance level of 0.05. The regression coefficient was then used to predict the trend of each ecological factor. The change of each social factor was calculated as difference of proportional data or change rate of non-proportional data between two selected years.

2.5. The effects of GTGP on social-ecological changes

We chose the degree of afforestation, which means the ratio of accumulative afforestation area to total area, to represent the degree of the GTGP (Fig. 1b). Partial correlation analysis is a widely applied statistical tool in ecological studies to isolate the relationship between two variables from the confounding effects of many correlated variables (Peng et al., 2013; Shen et al., 2015; Wu et al., 2015). Considering the ecological factors are affected by climate factors and revegetation (Lu et al., 2015), the degree of afforestation, annual precipitation and annual mean temperature were selected as independent variables. The partial correlation coefficient between each ecological factor and each independent variable was calculated, with the other two independent variables acting as control variables. In this way, we analyzed the effects of each variable on ecological factors at regional scale and identified significant ($p < 0.05$) influencing factor at county scale.

To figure out whether the social changes are relevant to GTGP, we used Pearson's correlation analysis to calculate the correlation coefficient between the change of each social factor and the degree of afforestation in 2014 at county level. Statistical significance of correlation coefficient was tested at a significant level of 0.05.

3. Results

3.1. Greening trend of NDVI after GTGP implementation

The trend of average AVHRR NDVI of the LP changed after 1999, the slope increased from 0.0018 yr^{-1} for 1982–1998 to 0.0053 yr^{-1} for 1999–2015 (Fig. 2a). Breakpoints in the NDVI time series were identified at pixel scale (Supplementary Fig. S3). The accumulated number of pixels with significant breakpoints increased from 1986 to 2011. Most breakpoints were detected between 1999 and 2002 (Fig. 2b) and showed a greening trend, which means the slope of the NDVI time series increased after the breakpoint. GTGP was launched in 1999 in the LP and fully implemented in most areas after 2000. Thus, we chose the year 2000 as the start year to illustrate the changes of the socio-ecological system on the LP.

MODIS NDVI from 2000 to 2015 as the state-of-the-art satellite product was also analyzed for comparison (Fig. 2c). Average NDVI of the LP increased significantly from 2000 to 2015 at a slope of 0.0100 yr^{-1}. At pixel scale, the annual NDVIs of most areas showed significant increasing trends, only few pixels in the urban areas showed a decreasing trend (Fig. 3a), which means the LP is greening after GTGP implementation.

3.2. Ecosystem services improved with the greening trend

Total soil erosion of the LP showed a significant decreasing trend of 0.96×10^8 t yr^{-1} during 2000 to 2015 (Fig. 2d), and significant decreases of soil erosion were mainly found in east and south LP (Fig. 3b). The decline of soil erosion is accompanied by a decrease in the sediment load of the middle reach of the Yellow River across the LP. The sediment load between the Toudaoguai station and Tongguan station decreased significantly by 0.25×10^8 t yr^{-1} during 2000 to 2015 (Fig. 2d). These results show the improvement of soil retention service on the LP.

Carbon sequestration service of the LP has also been enhanced after the large-scale vegetation restoration. The NEP of the LP increased significantly by 2.11 g C m^{-2} yr^{-1} during 2000 to 2015 (Fig. 2e). Most areas of the LP showed significant increasing trends of NEP (Fig. 3c). Total carbon sequestration by the ecosystem on the LP increased from 33.2 Tg C in 2000 to 45.2 Tg C in 2015, meaning the carbon sink of the LP has enhanced.

The ET time series of the LP from 2000 to 2014 showed an increasing trend of 1.30 mm yr^{-1} (Fig. 2f), and the increasing trend was significant in some areas on the central and southwestern LP (Fig. 3d). Meanwhile, runoff coefficient between the Toudaoguai station and Tongguan station decreased during 2000 to 2015 (Fig. 2f). These results indicate that the water supply service of the LP was affected.

3.3. Increases in the grain output

GTGP converted farmland on steep slopes to forest or grassland, resulting in a decline in the area of arable farming (area of cultivated land in Shanxi, Shaanxi, and Ningxia province declined 15.0% from 2000 to 2015). We compared the statistics of the grain output of 315 counties in 2000 and 2015 to investigate whether the food supply and security of the LP was affected after GTGP (Fig. 3e). The result shows that the total grain output of the LP increased 56.7%, from 2.96×10^7 t (where t indicates metric ton) in 2000 to 4.64×10^7 t in 2015 (Fig. 4a). However, changes in grain output differed among counties,

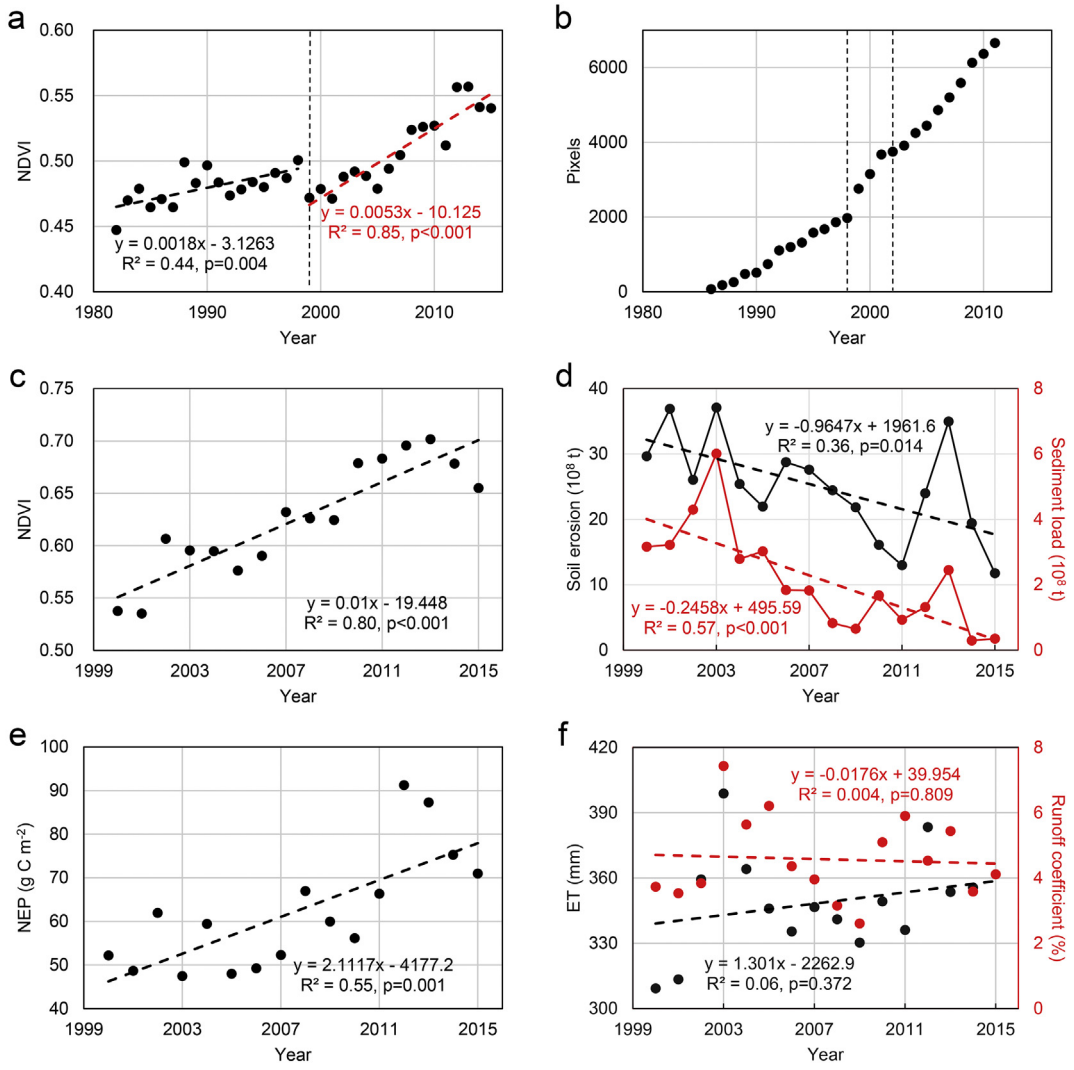

Fig. 2. Temporal profiles of ecological factors of the LP. (a) GIMMS NDVI (1982–2015). (b) Accumulated breakpoints in GIMMS NDVI time series. (c) MODIS NDVI (2000–2015). (d) Soil erosion of the LP and sediment load between the Toudaoguai station and Tongguan station on the Yellow River (2000–2015). (e) NEP of the LP (2000–2015). (f) MODIS ET of the LP (2000–2014) and runoff between the Toudaoguai station and Tongguan station on the Yellow River (2000–2015).

with 21.3% of these counties showing a decrease in grain output — these counties are mainly distributed in the south and central part of the LP (Fig. 3e).

3.4. Progress in socioeconomic development

Besides grain output, many other socioeconomic factors on the LP showed major changes after 2000. The gross output value of AFAHF increased by 164.5%, from 2.35×10^{11} yuan in 2000 to 6.22×10^{11} yuan in 2015 (2015 price) (Fig. 4b). Almost all the counties in LP showed increases in the gross output value of AFAHF (Fig. 3f).

The changes in population and rural employment on the LP were also analyzed (Fig. 3g, h). From 2000 to 2010, the total population of the LP increased from 101 to 110 million, urban population increased from 36 to 53 million (Fig. 4c). Urbanization rate of the LP increased from 35.3% to 48.5% (Fig. 4d). From 2000 to 2015, the number of rural employees increased from 33 to 36 million, AFAHF employees decreased from 24 to 21 million (Fig. 4e). The AFAHF proportion of rural employees decreased from 72.3% in 2000 to 57.9% in 2015 (Fig. 4f). The urbanization rate of the LP improved, and less people were engaged in AFAHF after 2000.

3.5. Changes of ecological factors mainly reflect the degree of afforestation

The effects of the degree of afforestation, annual precipitation, and annual mean temperate on ecological factors were analyzed by partial correlation analysis (Table 1). Overall, our results suggest that GTGP contributed significantly to the changes of NDVI, soil erosion, and NEP. For NDVI and NEP, partial correlation coefficients for the degree of afforestation are significantly positive. For soil erosion, partial correlation coefficient for the degree of afforestation is significantly negative whereas partial correlation coefficient for annual precipitation is significantly positive. For ET, partial correlation coefficient for annual precipitation is significantly positive. We also identified significant influencing factors of each ecological factor at each county (Fig. 5). The ratio of counties significantly influenced by afforestation to counties with significant influence factors for NDVI, soil erosion, and NEP is 92.1%, 68.1%, and 86.3%, respectively, which means afforestation is the main influencing factor of NDVI, soil erosion, and NEP in most areas. However, the distribution of influencing factors of ET is more complex. Considering that precipitation and temperature of the LP showed no significant change from 2000 to 2015 and only a few counties showed significant changes in the two factors (Supplementary Fig. S4), it is clear that the changes of

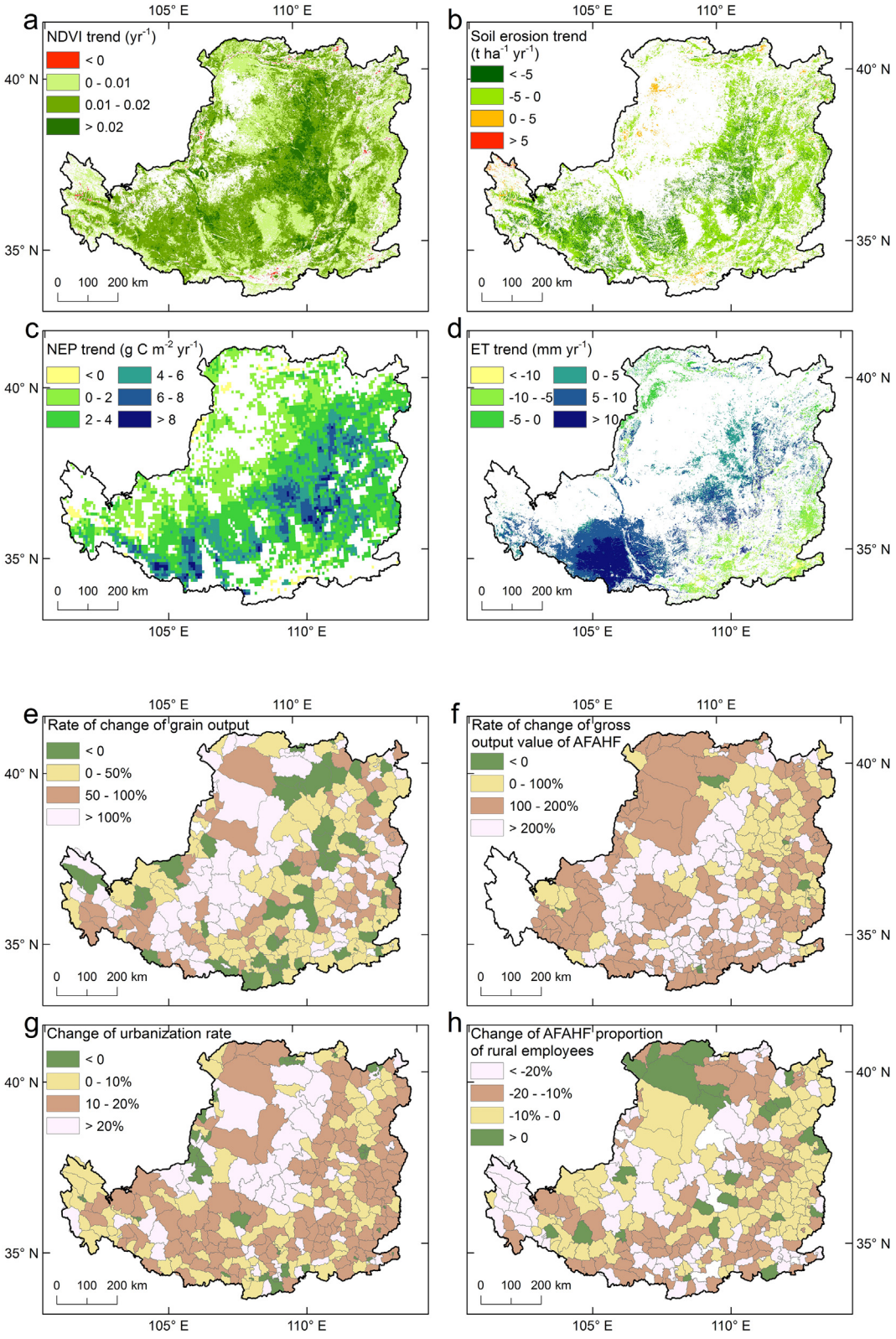

Fig. 3. Spatial distribution of the changes in social-ecological factors on the LP. (a) Significant MODIS NDVI trends ($p < 0.05$) from 2000 to 2015. (b) Significant soil erosion trends ($p < 0.05$) from 2000 to 2015. (c) Significant NEP trend ($p < 0.05$) from 2000 to 2015. (d) Significant MODIS ET trend ($p < 0.05$) from 2000 to 2014. (e) Rate of change of grain output from 2000 to 2015. (f) Rate of change of gross output value of AFAHF from 2000 to 2015. (g) Change of urbanization rate from 2000 to 2010. (h) Change of AFAHF proportion of rural employees from 2000 to 2015.

ecological factors mainly reflected the degree of afforestation rather than climate change.

As for social factors, the degree of afforestation has positive correlation with gross output value of AFAHF and urbanization rate and negative correlation with grain output and AFAHF proportion of rural employees (Table 1). However, only the correlation with gross output value of AFAHF was significant, the impacts of GTGP on social factors are clouded.

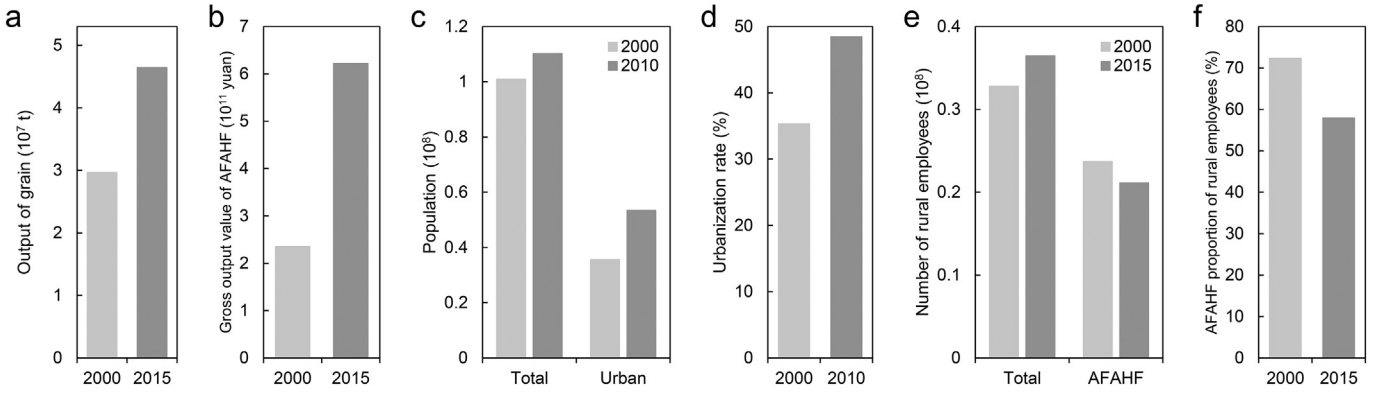

Fig. 4. Comparisons of socioeconomic factors. (a) Grain output of the LP in 2000 and 2015. (b) Gross output value of AFAHF of the LP in 2000 and 2015. (c) Total and urban population of the LP in 2000 and 2010. (d) Urbanization rate of the LP in 2000 and 2010. (e) Number of total and AFAHF rural employees of the LP in 2000 and 2015. (f) AFAHF proportion of rural employees of the LP in 2000 and 2015.

4. Discussion

4.1. LP gained both green and grain

Monitoring assessments and statistical results show that the LP has achieved "win-win" gains of restoring the environment and promoting socioeconomic development, experiencing a shift from poor green and poor grain to more green and more grain. NDVI time series showed a greening trend, and soil retention and carbon sequestration services improved significantly from 2000 to 2015. Our results indicate that the revegetation on the LP has had significant impact on vegetation cover, soil erosion, and carbon stocks, these findings are consistent with previous studies (Lu et al., 2012; Ouyang et al., 2016; Tong et al., 2018). The breakpoints detected in NDVI time series fit well with the implementation and spatial extent of GTGP. Analyses show that the ratio of afforestation area to total county area significantly affects the changes of NDVI, soil erosion, and carbon sequestration. Previous research was concerned with the effects of the expansion of GTGP on the availability of farmland and the impacts on local food supply, arguing that too much grain has been traded for green (Y. Chen et al., 2015). However, our results show that grain output of the LP was enhanced in the period of 2000–2015. Considering the correlation of the GTGP and grain output is insignificantly negative, some other factors may result in the increase of grain output.

We selected Shaanxi, Shanxi, and Ningxia province to figure out why grain output increased by 30.2% while the area of cultivated land decreased by 15.0% and sown area of crops decreased by 8.8% (Table 2). Firstly, the development of agricultural facilities and the application of modern technologies improved grain output per hectare. For instance, from 2000 to 2015, total power of agricultural machinery, irrigated area of cultivated land, and consumption of chemical fertilizers in agriculture of the three provinces increased 119.2%, 13.9%, and 61.5%, respectively. As a result, grain output per hectare improved 42.7% (Table 2). Secondly, grain yield of the steep farmland that was removed from cultivation by the project contributed relatively little to the total grain output, with the resulting decrease in total grain output being offset by the improved grain yield in more suitable land (Cao, 2011). Furthermore, new civil engineering work brought more land on the LP into productive agricultural use. For instance, the Ministry of Land and Resources in China launched the Gully Reclamation Project on the LP in 2012. This project reclaimed 33.78×10^3 ha of cropland between 2013 and 2017 (Wang et al., 2018). Gullies were filled to create farmland. Food security was improved while achieving the double benefits of ecological restoration and efficient use of land resources (Liu et al., 2013).

Table 1
Correlation coefficients of each social-ecological factor and independent variables. The coefficients of ecological factors were calculated by partial correlation analysis.

	Factors	Degree of afforestation	Precipitation	Temperature
Ecological factors	NDVI	0.87^{***}	0.39^{ns}	-0.16^{ns}
	Soil erosion	-0.64^{*}	0.73^{*}	0.39^{ns}
	NEP	0.69^{*}	0.18^{ns}	-0.19^{ns}
	ET	-0.55^{ns}	0.74^{**}	-0.57^{ns}
Social factors	Grain output	-0.05^{ns}	–	–
	Gross output value of AFAHF	0.15^{*}	–	–
	Urbanization rate	0.04^{ns}	–	–
	AFAHF proportion of rural employees	-0.08^{ns}	–	–

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; ^{ns} non-significant at 0.05 level.

4.2. Socioeconomic effects of GTGP

Our results suggest that the gross output value of AFAHF and urbanization rate of the LP improved, less people were engaged in AFAHF after 2000. However, the effects of GTGP on changes of social factors are mainly insignificant. This is because that the specific impacts of GTGP are often clouded by the confounding effects of multiple socioeconomic, policy and environmental factors operation concurrently (Ouyang et al., 2016; Bryan et al., 2018). For example, in addition to the GTGP, economic development, urbanization, and industrialization have also played important parts in the social changes of the LP. On the other hand, previous studies suggested that GTGP helped numerous farmers to change their income structure by shifting from farming to other activities (Liu et al., 2008; C. Chen et al., 2015), and has generated a large number of surplus laborers and prompted many of them to seek jobs in cities (Liu et al., 2008), driving the process of urbanization and spreading the benefits of rapid economic development. Furthermore, Pearson's correlation analysis used in our study just reflects correlation rather than causality among variables. Thus, a comprehensive and robust quantitative evaluation of the specific impacts of GTGP by causal methods is needed (Bryan et al., 2018). Such an evaluation should not only capture the effects of GTGP, but also reveal the underlying pathways or processes through which GTGP affect socioeconomic outcomes (Yang et al., 2018).

4.3. Ecosystem services and their relationships

Ecosystem services resulting from the environmental rehabilitation of the LP have also benefited other areas, both nearby and remote. We

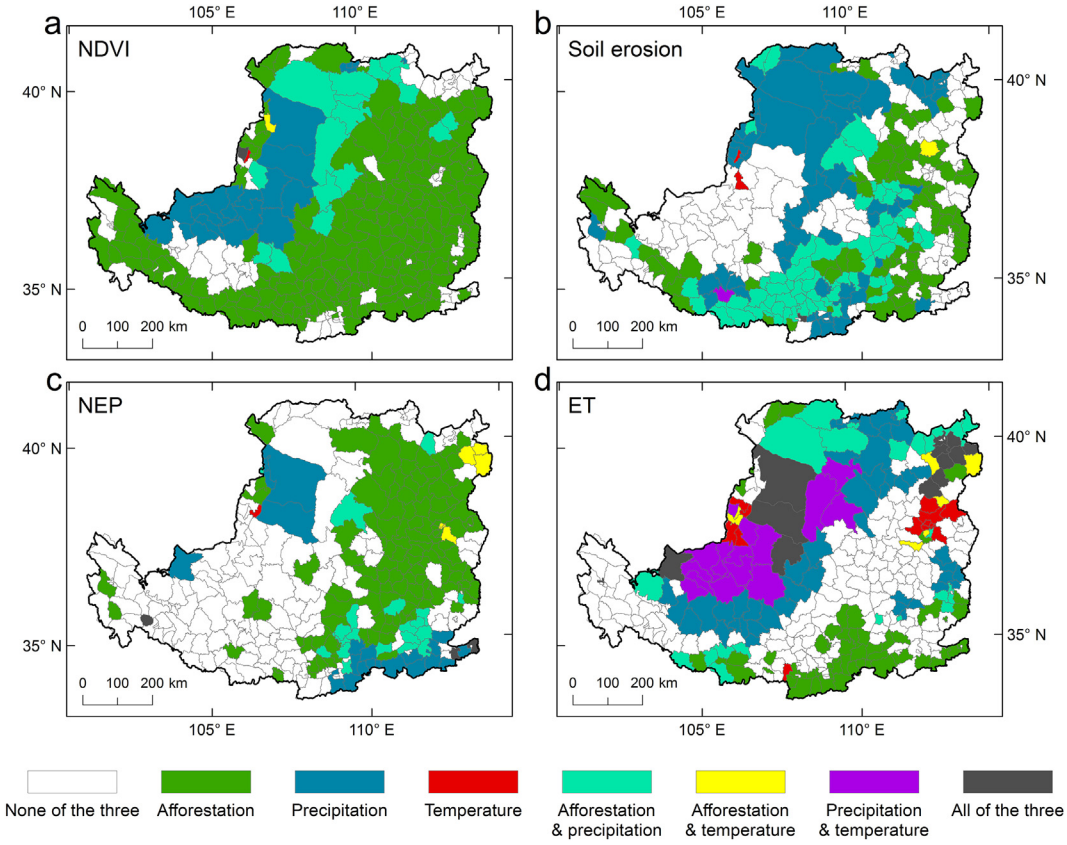

Fig. 5. Significant influencing factors ($p < 0.05$) of each ecological factor at each county identified by partial correlation analysis. (a) MODIS NDVI. (b) Soil erosion. (c) NEP. (d) ET.

found that the decline of soil erosion in the LP is accompanied by a decrease in the sediment load of the middle reach of the Yellow River, which solved the problems that have plagued the Yellow River for hundreds of years (Wang et al., 2015). We found carbon sequestration of the LP has been enhanced after the GTGP, which is consistent with previous research that declared the LP has also become an important carbon sink with global significance (Feng et al., 2013). However, there are complex relationships between different ecosystem services. In a water-limited area, the improved carbon sequestration and soil retention resulting from vegetation expansion are accompanied by increase of ET (Menz et al., 2013; Feng et al., 2016), causing negative consequences such as water yield reduction (Cao, 2011) and drying soil (Wang et al., 2011). Our results also show that the water supply service in the LP was affected. The LP is a water-scarce area. If we exceed the vegetation-carrying capacity of the ecosystem, it may result in unintended consequences, perhaps even a tragedy (Feng et al., 2016). The scientific understanding of the process of ecosystem services supply is the foundation of the PES policy design, and market or government regulation. Former policy was not tailored to local environmental conditions, leading to the planting of inappropriate species with an overemphasis on trees and shrubs, which in turn caused deterioration of soil ecosystem services and exacerbated water shortages (Cao et al., 2011). Fortunately, the new round of GTGP launched in 2014 emphasized the need for suitable revegetation types and the selection of species according to local environmental conditions.

Table 2
Agricultural conditions of Shanxi, Shaanxi, and Ningxia province in 2000 and 2015.

	2000	2015	Difference	Rate of change
Grain output (10^6 t)	21.95	28.59	6.64	30.2%
Grain output per hectare (t ha^{-1})	2.81	4.01	1.20	42.7%
Area of cultivated land (10^3 km^2)	109.98[a]	93.44	−16.54	−15.0%
Total sown area (10^3 km^2)	96.14	93.17	−2.97	−3.1%
Sown area of crops (10^3 km^2)	78.15	71.31	−6.84	−8.8%
Total power of agricultural machinery (10^6 kw)	31.25	68.50	37.26	119.2%
Irrigated area of cultivated land (10^3 km^2)	28.12	32.04	3.92	13.9%
Consumption of chemical fertilizers in agriculture (10^6 t)	2.42	3.91	1.49	61.5%

[a] Area of cultivated land in 2000 is the survey data of land use in 1996.

5. Conclusion

LP has achieved "win-win" gains of restoring the environment and promoting socioeconomic development after GTGP. NDVI time series showed a greening trend, and soil retention and carbon sequestration services improved significantly from 2000 to 2015. Simultaneously, grain output from the LP has increased. Analyses show that the degree of afforestation significantly affects the changes of NDVI, soil erosion, and carbon sequestration.

Specific socioeconomic impacts of GTGP are often clouded by the confounding effects of multiple socio-economic, policy and environmental factors operation concurrently. Our analyses just show the effects of GTGP on changes of social factors are mainly insignificant. Further research should consider multiple factors and evaluate the social impacts of GTGP comprehensively and quantitatively.

Despite some adverse outcomes, GTGP in LP has achieved considerable overall success in environmental factors. Timely feedback for adjusting and refining PES based on scientific evidence is necessary. To improve the likelihood of "win-win" outcomes that advance both environmental and socioeconomic goals, the implementation of PES program should be combined with other measures. In our study, food security of the LP was ensured by the development of agricultural

facilities and technologies and using civil engineering to create new farmland suitable for cultivation.

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Author contributions

B.F. designed the research. X.W., S.W. and B.F. wrote the manuscript. X.W. conducted statistical analysis. All the authors contributed to the writing of the manuscript.

Competing interests

The authors declare no competing financial interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.05.022.

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